Potential fields methods for location of unexploded ordnance (UXO)

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Millions of acres of land, formerly and currently used for military training, and testing ranges are potentially contaminated by surface and buried unexplored ordnance (UXO). Surface and buried UXO exists at hundreds of sites with diverse geologic and environmental conditions. UXO exist from the surface to depths as great as 10 m and range in size from 20-mm projectiles to 2000-lb bombs (Figure 1). UXO cleanup is currently the highest priority U.S. Department of Defense environmental quality issue at Base Realignment and Closure (BRAC) sites and Formerly Used Defense Sites (FUDS). UXO cleanup is also required at active test and training ranges for continued safe utilization of existing facilities.

The most frequently used methods for UXO location surveys are total field magnetometers (TFM) and "simple" time domain electromagnetic induction (TDEM) instruments. Simple TDEM loosely refers to systems that measure 1-2 time windows (gates) from the induced transient decay signal. When used by experienced geophysical practitioners during demonstrations at controlled UXO test sites, probabilities of detection of UXO exceed 90%. Generally, for production surveys at large sites, only one of these systems will be deployed.

Other geophysical methods proposed, demonstrated, and/or utilized for UXO surveys are ground penetrating radar (GPR), frequency domain electromagnetic induction (FDEM), multigate TDEM, multicomponent TDEM, multicomponent (vector) magnetometers, magnetic gradiometers, acoustic/seismic methods, gravimetry, and airborne systems of various types. GPR is not an applicable tool or approach for large-area UXO detection surveys. However, GPR has applicability and considerable potential for small-area UXO discrimination and identification efforts after UXO has been located by other methods. Efforts to apply airborne geophysical surveys for UXO location at heights typically greater than 25 m, including magnetometry, GPR, and SAR, have been failures. Recently, however, TFM and simple TDEM surveys from a helicopter platform at 1.5-2.5 m elevation have shown promise for large-area UXO detection surveys, detecting areas of UXO concentration, and larger individual ordnance items. Multigate, multicomponent TDEM systems and multifrequency FDEM systems have potential for large-area UXO detection surveys and possibly for near real-time discrimination or follow-on small-area discrimination of detected anomalies.

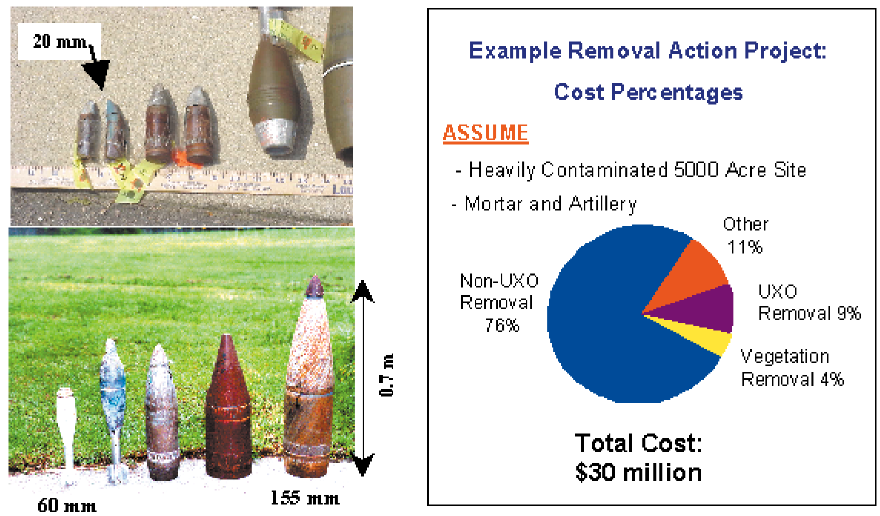

Figure 1. Typical ordnance items and cost distribution for UXO cleanup.

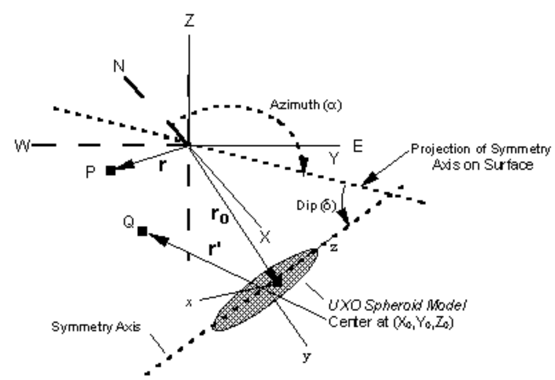

Figure 2. Geometry for UXO model development.

Like GPR, some of these approaches will have very limited applicability to large area detection surveys, but may contribute to small area surveys for discrimination. Gravimetry and seismic/acoustic methods, in particular, are likely to have a very limited, niche role (or no role at all) for small-area UXO surveys. If gravity surveys and in particular microgravity surveys can measure the gravitational anomaly produced by buried UXO, the results can be used to estimate the UXO mass. No other approach currently applied to UXO detection and discrimination directly gives a mass estimate. The induced TFM anomaly is independent of ferrous mass and is determined by the contained ferrous volume, the shell thickness, length to diameter ratio, magnetic permeability, and the orientation in the earth's magnetic field (Altshuler, UXO Forum 1996). Joint inversion of TFM and microgravity data sets for a geometrically consistent model could yield mass and volume and thus a density estimate. The density estimate could serve as a UXO discriminant, because the UXO bulk density will be less than that of solid steel. Realistically, however, microgravity surveys will have potential only for UXO discrimination and identification with small-area surveys of objects located by other methods and then only for large UXO items.

This paper illustrates some ongoing efforts to develop forward and inverse modeling tools for UXO discrimination, specifically analytical solutions for the gravity and magnetic responses for realistic, geometrically

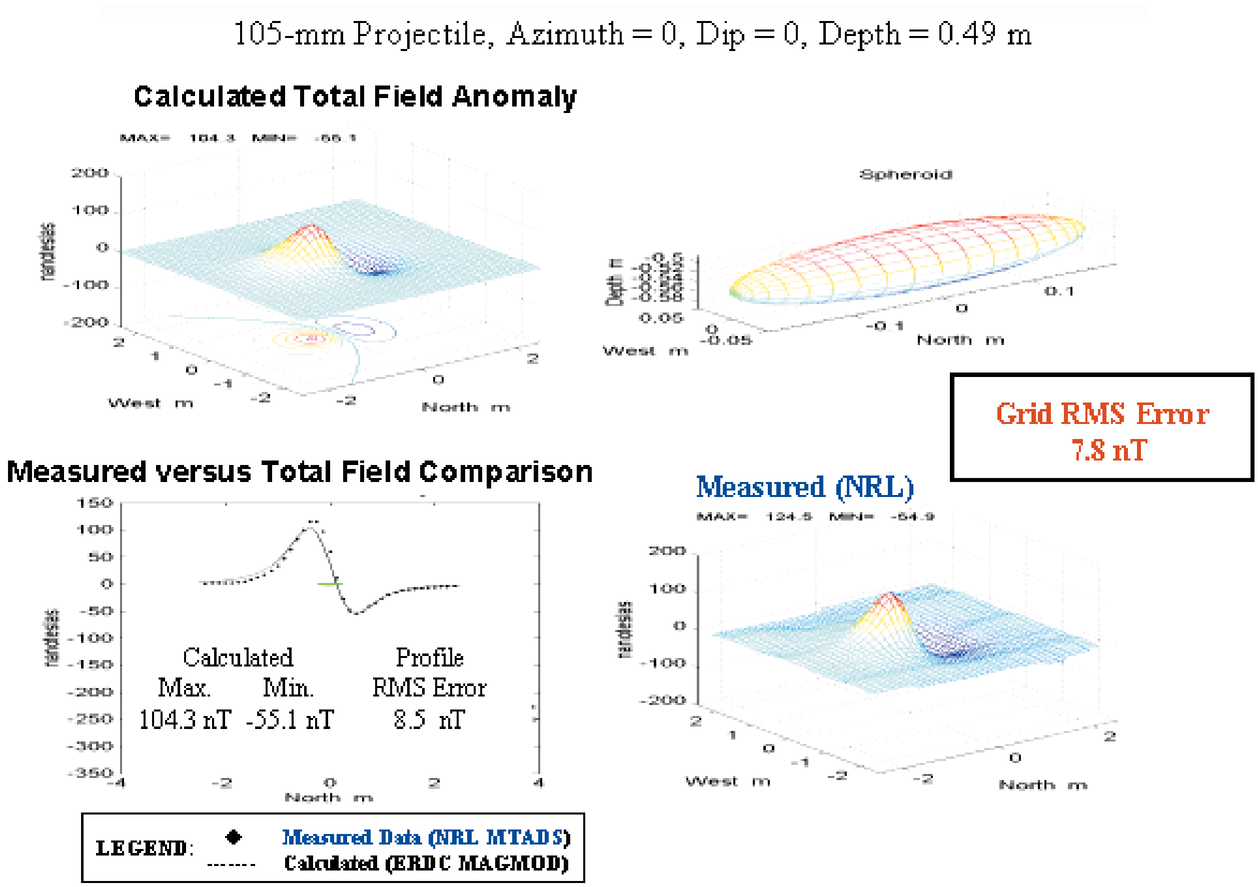

Figure 3. Comparison of measured (Naval Research Laboratory) and calculated (MAGMOD) total magnetic field for a 105-mm projectile.

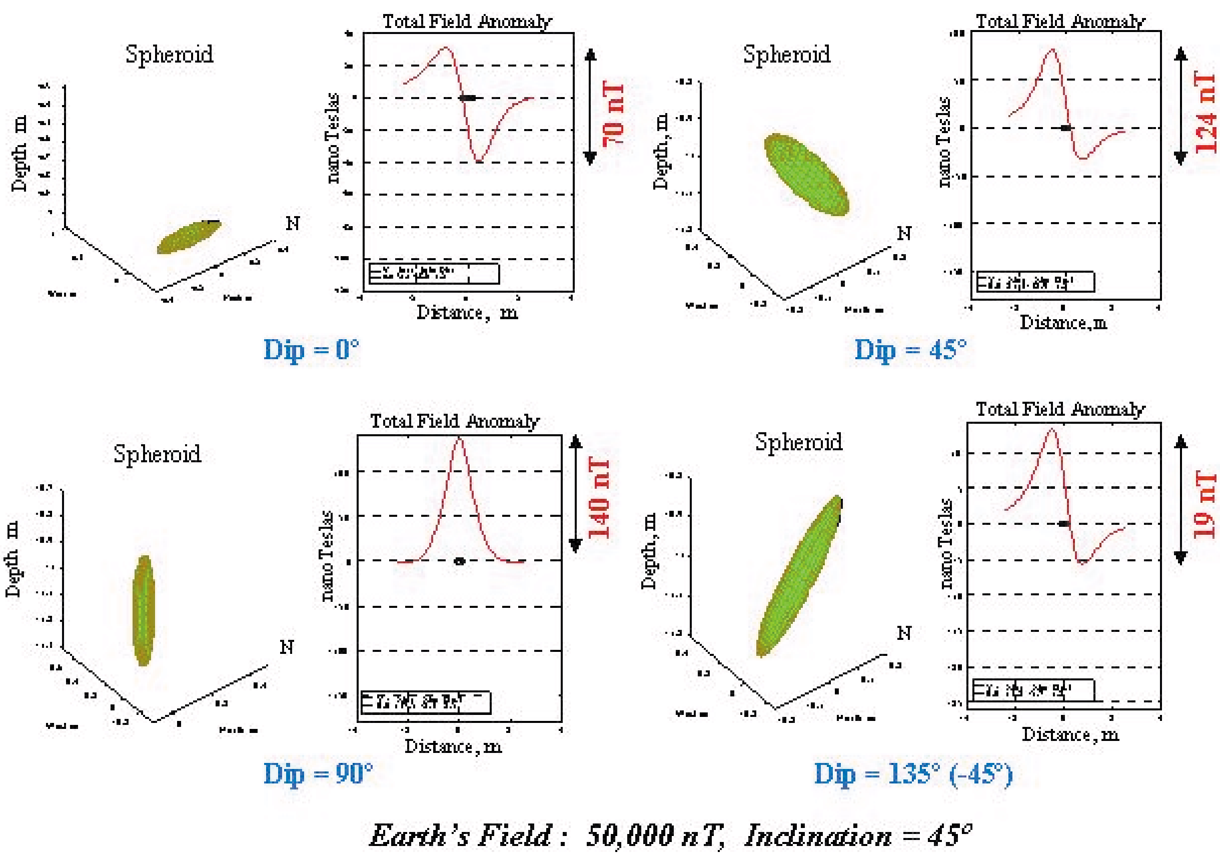

Figure 4. The effect of dip on the total magnetic field anomaly for a 105-mm projectile model.

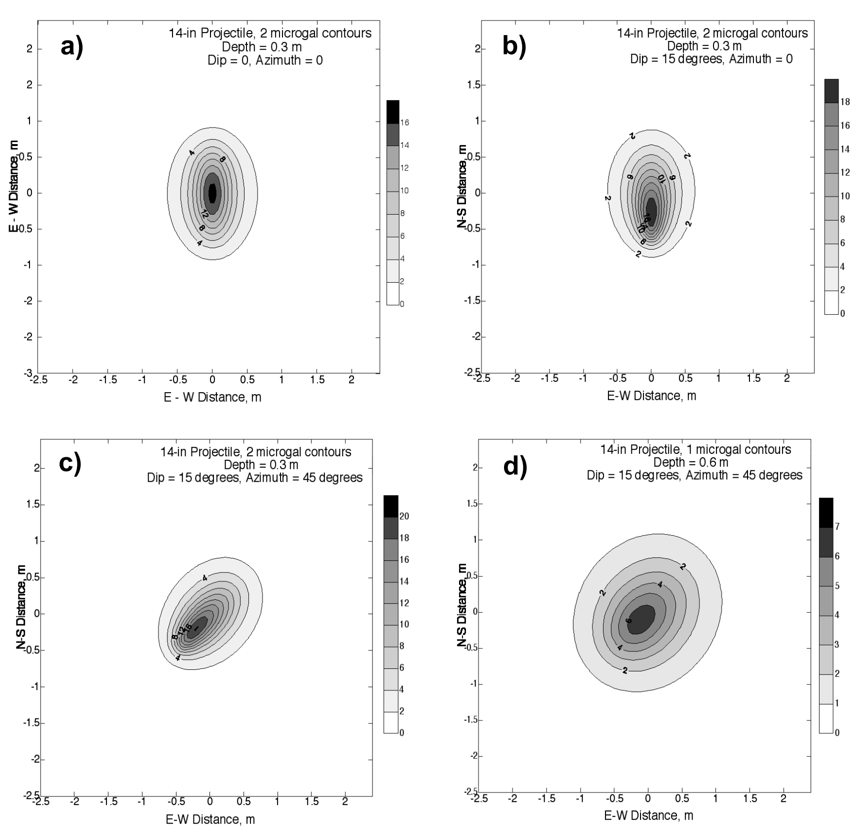

Figure 5. Gravity anomalies above a 14-inch projectile spheroid model for the cases: (a) depth = 0.3 m, dip = 0, azimuth = 0; (b) depth = 0.3 m, dip = 15°, azimuth = 0; (c) depth = 0.3 m, dip = 15°, azimuth = 45°; (d) depth = 0.6 m, dip = 15°, azimuth = 45°.

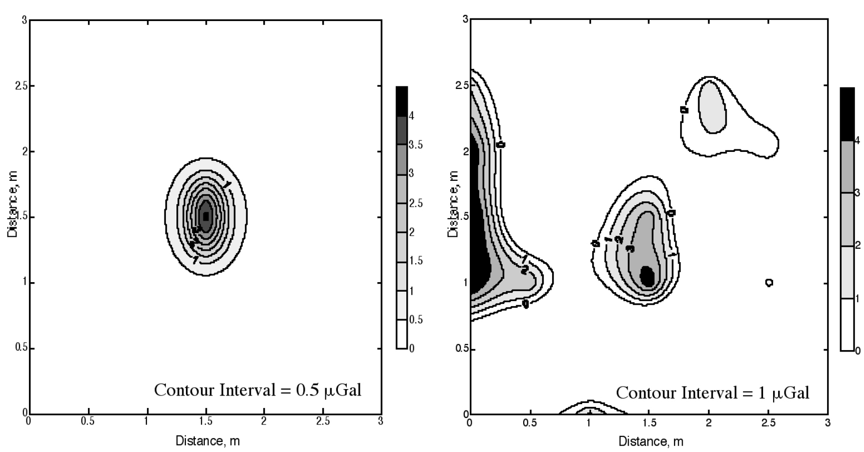

Figure 6. Calculated (left) and measured (right) gravity anomalies over a 155-mm projectile, oriented approximately horizontal with nose pointing north. Depth = 9 cm to top of projectile; length = 0.637 m; diameter = 0.155 m; mass = 45.25 kg mass; and measurement spacing = 0.5 m.

consistent UXO models. The prolate spheroid, a special case of a general ellipsoid, is selected as an appropriate UXO model for analytical development. TFM and gravity model predictions are compared with measurements. Examples in this paper are some of the highest resolution potential fields data sets ever obtained (TFM data with 25-cm line spacing and 10 cm along lines; microgravity measured on a 50 × 50 cm grid). Concomitant with the requirements for high fidelity measurements and large data volume management are exacting positioning and navigation capability for subsequent location of anomaly sources.

Models for UXO magnetic and gravity response. The prolate spheroid model is a realistic representation of the general shape of ordnance and also has the elongated geometry of ordnance that can replicate demagnetization and orientation effects. A prolate spheroid with the length and diameter of an ordnance item is a good approximation to the outer ferrous volume of the ordnance. The induced magnetic field external to a spheroid can be determined by a full field solution or a multipole expansion. The multipole expansion has no monopole term and the quadrapole term is zero due to symmetry. Thus, an octupole term is the next higher term after the dipole term and, since the octupole term falls off as $1/r^5$, there is no practical reason to include anything higher than the octupole term. Altshuler (UXO Forum, 1996) compares the dipole field (for a spheroid model) with the full field solution and concludes that, for measurement distances greater than about two semimajor axes (the length) from the center of volume of the spheroid, the dipole model field prediction is within 10% of the full field model prediction. Thus for small distances, the octupole field contribution becomes more significant. Advantages of a multipole solution compared to a full field solution are (a) slightly reduced computational time and (b) ability to separate the prolate spheroid dipole term for comparison with the dipole solution for a sphere or an oriented dipole solution. The primary disadvantage is a possible lack of accuracy for very close distances of the model to the signature calculation plane.

Available gravity modeling approaches are not readily applicable to buried UXO. Some approaches make inappropriate geometrical assumptions, such as two-dimensionality of the sources, or require a complex parameterization of the source geometry, such as approximation of its surface by triangular planar facets or a complete discretization of the UXO source body. As mentioned previously, a reasonable approximation to the actual shape of the ordnance is obtained by a prolate spheroid. Relatively few parameters are required to specify each spheroid: length, diameter, dip angle, azimuth, and density contrast. A closed-form expression for the gravity field of general homogeneous ellipsoids (of which the spheroid is a special case) is known in terms of elementary functions. Thus, computing the gravity response of homogeneous spheroids should be

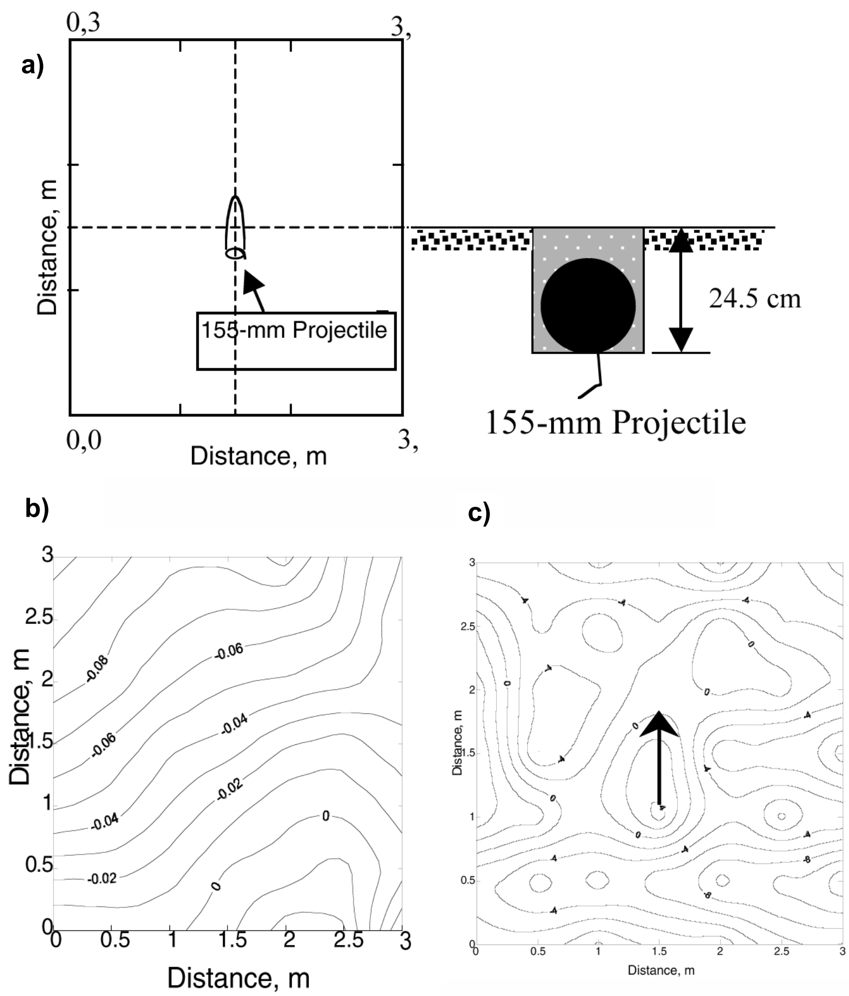

Figure 7. Site layout (a), topography (b), and relative Bouguer anomaly map (c).

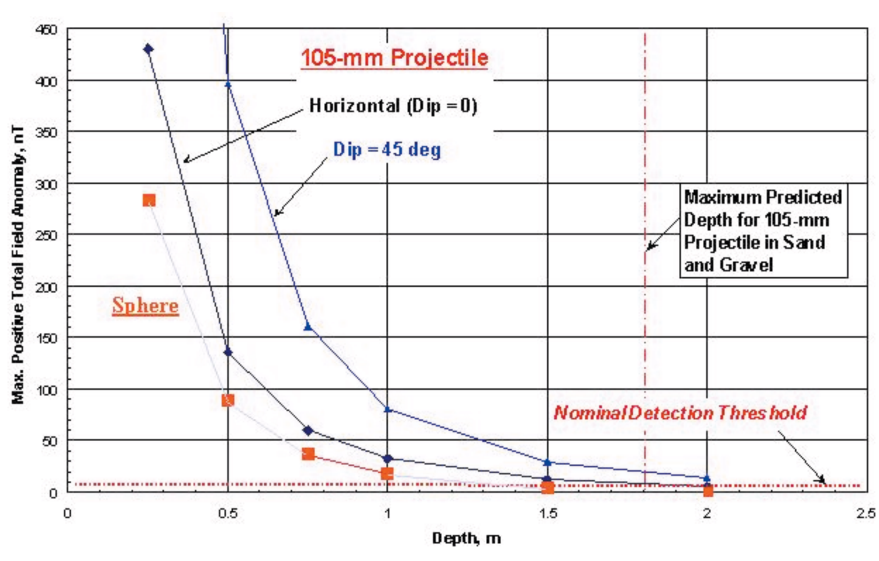

Figure 8. Maximum positive total field anomaly as a function of depth for two orientations of 105-mm projectile model and equivalent volume sphere.

straightforward. However, no software for modeling the gravity response of prolate spheroids existed. The prolate spheroid modeling capability for UXO was developed as an aid in evaluating the usefulness of gravity measurements in detecting unexploded ordnance. The geometry for the magnetic and gravity model development is shown in Figure 2. Further details of the model development and examples are presented in Butler et al. (*Journal of Environmental and Engineering Geophysics*, 2001).

Magnetic modeling examples. Input to the UXO magnetic modeling program includes specification of the calculation grid, the earth's magnetic field (magnitude, inclination, and declination), relative magnetic permeability of model, spheroid length and diameter, spheroid dip and azimuth, horizontal position coordinates of the spheroid center, depth to the center, and measurement height (calculation plane height above Z=0). The program has been validated by comparison to measured TFM measurements over buried UXO. Figure 3 is an example of a validation in which the measured data were acquired by the Naval Research Laboratory (Nelson et al., UXO Forum, 1997). The example in Figure 3 is for a horizontal, N-S oriented 105-mm projectile at a depth of 0.54 m to center and measurement height of 0.25 cm. The earth's field magnitude is 53 600 nT and has inclination of 67.10 at the measurement site and for the calculations.

The effect of UXO (spheroid) orientation on magnetic signature is illustrated in Figure 4 which shows the signatures of a 105-mm projectile model at four dip angles. Significantly, the signatures vary from nearly symmetric dipolar to asymmetric dipolar to nearly monopolar. The magnitudes of the signatures (as measured from minimum to maximum) vary from 19 nT to 140 nT. The maximum magnitude occurs when the long axis of the spheroid is parallel to the earth's field (maximum induction), while the minimum magnitude occurs when the long axis is perpendicular to the earth's field. A key implication of the dramatically different signature shapes and magnitudes in Figure 4 is that simple dipole (sphere) interpretations of the anomalies will give different source depths and sizes for the same UXO model.

Gravity modeling examples. The bulk density of ordnance items varies from ~3.3 g/cm^3 to >6 g/cm^3. For a typical soil density of 2 g/cm^3, the density contrast will vary from ~1.3 g/cm^3 to >4 g/cm^3. The features of the gravity anomaly for a prolate spheroid model are intuitive, and are illustrated in Figure 5 for a 14-inch projectile (length = 1.48 m, diameter = 0.356 m, density = 6.6 g/cm^3). For a horizontal spheroid model, the gravity anomaly is symmetric about two horizontal axes

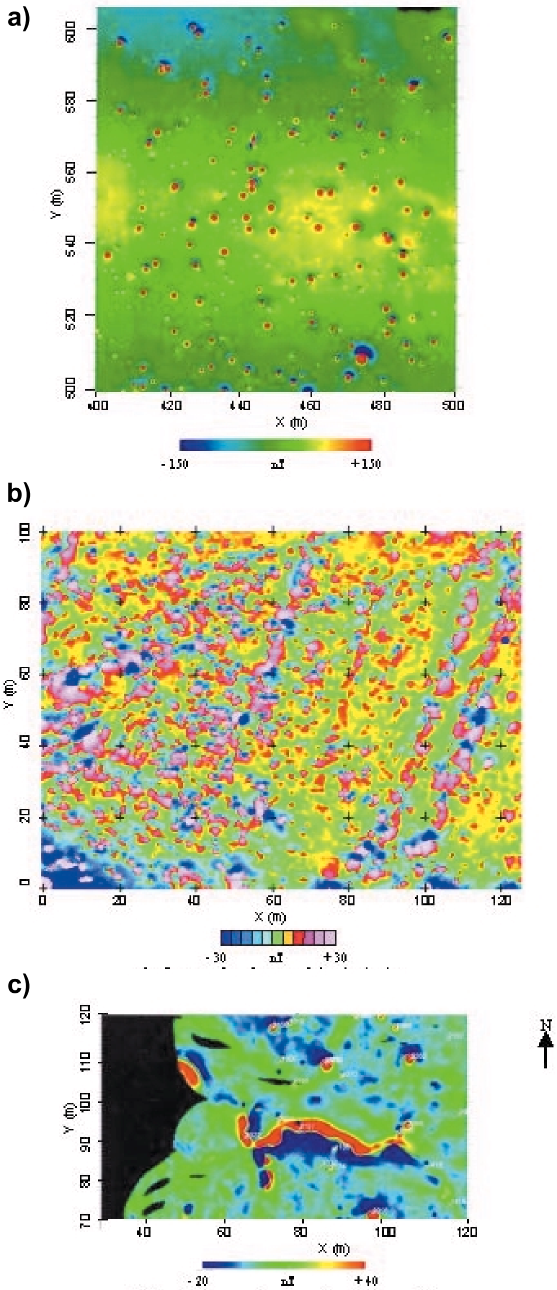

Figure 9. Examples of UXO magnetic anomaly detection or identification in three magnetic background settings: (a) low-noise site; (b) intensely cluttered (noisy) site; (c) site with prominent geologic anomalies.

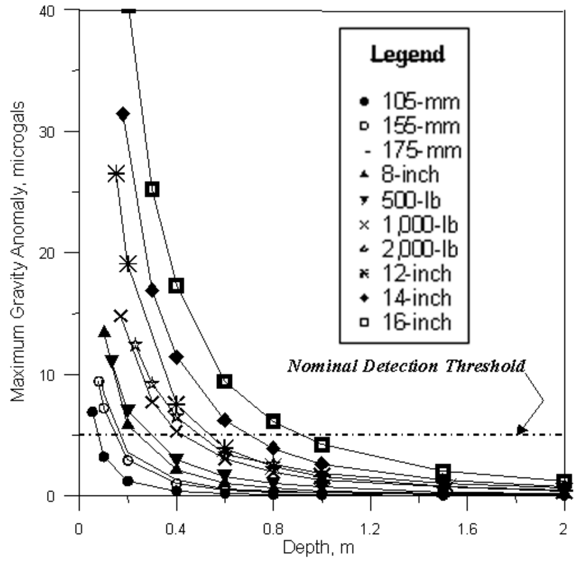

Figure 10. Maximum calculated gravity anomaly for 10 ordnance items.

(Figure 5a). As the dip increases from zero, the anomaly is symmetric only about the projection of the major axis of the spheroid on the surface (Figure 5b). Unlike the total field magnetic anomaly, which is induced by the earth's field, the gravity anomaly field for a prolate spheroid model of UXO follows (i.e., does not lag) the azimuth of the spheroid (Butler et al., 2001). The gravity anomaly is rotationally symmetric about a vertical axis as the spheroid azimuth varies (Figures 5b and 5c). Doubling the depth of the spheroid from 0.3 m to 0.6 m results in a peak field decrease from ~22 microgals to ~7 microgals (Figures 5c and 5d), along with the expected increase in anomaly width. The anomalies for the cases in Figure 5 will be detectable with a well-executed microgravity survey. However, a 14-inch projectile is quite large (comparable to a 1000-lb bomb in size, but with greater density).

Figure 6 compares calculated and measured gravity anomalies over a buried 155-mm projectile. Figure 7 gives the topography and general details of the survey site. Measurements were made on a 0.5-m grid over a 3 × 3 m area, centered on the buried projectile, with an EDCON Super-G Meter. Each measurement consists of the mean of at least five 15-s records, and the mean standard deviation of all measurements is 1.5 uGal. For ease in comparison with the calculated anomaly, only positive anomaly values are shown in the measured anomaly map. There is clearly a positive gravity anomaly approximately centered on the buried 155-mm projectile. While there are other closed anomalies in the survey area, the coincidence of the positive anomaly with the location of the projectile is likely not fortuitous (Figure 7c). The positive anomaly has approximately the correct spatial wavelength and magnitude. The measured anomaly has its maximum value near the shank end of the projectile, and the anomaly magnitude and spatial wavelength decrease near the nose end; these features are intuitive for the gravity response of a real projectile buried at very shallow depth. The calculated anomaly for the prolate spheroid model is centered over the symmetric model (i.e., no differentiation in nose and shank ends for the model).

Observations and implications. The forward modeling discussed in this paper of the magnetic and gravity anomaly signatures of prolate spheroid models for UXO is useful for parametric studies of the effects of ordnance orientation, ordnance size, depth, and earth's magnetic field strength and orientation (i.e., location). Summary plots allow detectability considerations for given ordnance items as a function of depth for limiting orientation cases. For example, Figure 8 presents the maximum positive total field magnetic anomaly value for a 105-mm projectile model as a function of depth for two orientations. Also shown are a nominal detection threshold and the maximum expected penetration depth for the 105-mm projectile in sand and gravel. A 105-mm projectile with azimuth = 0 and dip = 45° should be detectable to depths greater than the maximum expected penetration depth for sand and gravel, while the case for dip = 0° will be marginally detectable at the maximum penetration depth. Consideration of detectability of an ordnance anomaly in a given magnetic background setting is much more complicated than just exceedance of a constant threshold. A better assessment of detectability is a comparison of the power spectral density of the ordnance signatures relative to that of the background (Khadr et al., UXO Forum, 1997). Three examples of magnetic background settings are illustrated in Figure 9. Settings range from a very low-noise site (9a), to a very noisy, intensely cluttered site (9b), to a site with prominent geologic background anomalies (9c). For the low-noise site (9a), a simple constant threshold is adequate for detectability considerations. While spatial wavelength filtering might be used for UXO detection in the presence of localized geologic anomalies (9c), UXO detection with magnetometry in a highly cluttered environment (9b) will be extremely difficult if not impossible.

The situation is similar for gravity anomalies. Figure 10 is a summary plot of maximum gravity anomaly value versus depth for 10 ordnance item models (oriented horizontally). The ordnance item models range from 105-mm projectiles to 16-inch projectiles and 2000-lb bombs. Significantly, all ordnance items produce maximum anomalies that are detectable for cases where the items are very shallow (i.e., just below the surface). For the smaller ordnance items, the small spatial wavelength of the anomaly would require very closely spaced measurements to characterize the anomaly. Only two of the items have maximum anomaly values exceeding 5 microgals at 0.5-m depth; and at 1.0-m depth, only the 16-inch projectile has an anomaly value ~5 microgals. An obvious, practical implication of the data in Figure 10 is that microgravity is not likely to contribute to UXO discrimination and identification. One factor that is not included in the gravity anomaly model considerations is the "halo" of compressed (higher density) soil around the buried UXO due to the penetration process. The halo is likely to have a volume comparable to the UXO itself, and the presence of the halo cannot be duplicated in a UXO test site where the ordnance items are buried in excavations.

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